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A.~~TRANSIT DELAY AND JITTER CALCULATIONS IN A NETWORK~~A
A.Field of the Invention

5 The invention relates to networking technology and more specifically, to methods for determining network performance.

Background to the Invention

10 A communications network is increasingly becoming the foundation upon which many applications and services are built. The classic example of such a popular communications network is the Internet upon which, among other things, a whole new field of business termed e-commerce is based. Even within a local
15 environment, a communications network is used for applications such as electronic mail for the dissemination of information within an organization. The quality of applications and services running over these networks is dependent on the quality of service
20 provided by the underlying networks. This creates a need for automatic methods of measuring a network's quality. One such measure of the quality of a network is the delay in communication between a pair of devices in the network. Another measure is jitter - this
25 measures the variance of this delay. Depending on the application, either delay measurements or jitter measurements or both may be of interest. For example, in Voice over IP (Internet Protocol) applications, not only is delay important but jitter as well - two users
30 communicating by voice over the network should not experience a lag in communication, nor should they

experience abrupt pauses in their conversation. Methods which perform these measurements can be used by a network administrator who is interested in evaluating or monitoring a network to ensure it meets the criteria for the deployment of an application over the network.

Ideally, such measurements are made remotely or from a specific fixed node in the network. This avoids the need for each node in the network to measure its own performance. Such individual piecemeal measurements would contribute to a degradation of network performance and potentially adversely affect the measurement results.

One tool which can be of use in performing such measurements is the topology of the network. Methods of determining the topology of a network are known in the art such as that described by Dawes et al in US Patent 5,933,416 and US Patent 5,926,462.

Accordingly, there is a need for methods which can be used to automatically measure network performance. Ideally, such methods would take advantage of the knowledge of the topology of the network.

Summary of the Invention

The present invention includes methods which determines network performance by determining not only the transit delay between nodes in a network but also the variance, or jitter, of such transit delays. A common node, usually a network management computer (NMC), sends out a signal to a first node of interest and measures the time before it receives an acknowledgment from the first node. The NMC then sends out a similar signal to a second node of interest and similarly measures the time required to receive an

acknowledgment. Based on these two measurements, the transit delay between the first and second nodes can be calculated if the first node lies on the path between the NMC and the second node or vice versa. For a
5 multiple node communications path, the total transit delay between any two nodes is the sum total of the transit delays between adjacent nodes lying on the path. In the case of meshed networks, where a path to a node may be ambiguous, additional measurement nodes
10 strategically positioned in the network can be used such a way that the transit delay between any adjacent pair of nodes can be calculated unambiguously from at least one of these measurement nodes, i.e., the portion of the network being measured will be reduced to a hierarchical
15 one with respect to at least one of the measurement nodes.

In a first embodiment, the invention provides a method of determining a transit delay between a first node and a second node in a hierarchical segment of a
20 network connected to both the first node and the second node, the method comprising:

a) sending a first signal from a common node to the first node;

b) receiving a first response signal at the
25 common node from the first node in response to the first signal;

c) determining a first round trip time, the first round trip time being the time elapsed between steps a) and b);

d) sending a second signal from the common
30 node to the second node;

e) receiving a second response signal at the common node from the second node in response to the second signal;

5 f) determining a second round trip time, the second round trip time being the time elapsed steps d) and e); and

g) calculating the transit delay between the first node and the second node according to the formula

$$D(X,Y) = |R(NMC,X) - R(NMC,Y)|/2$$

10 where

D(X,Y) is the transit delay between first node X and second node Y;

R(NMC,X) is the first round trip time;

15 R(NMC,Y) is the second round trip time; and NMC is the common node.

In a second embodiment, the invention provides a method of determining a total transit delay between a start node and an end node in a network the method comprising:

20 a) determining interim transit delays between adjacent nodes in a communications path between the start node and the end node; and

25 b) calculating the total transit delay between the start node and the end node by adding up the interim transit delays. In the case where multiple paths may exist between the start node and the end node, separate total transit delays will be associated with each possible path.

30 In a third embodiment, the invention provides a method of determining the quality of communications between two nodes in a network, the method comprising:

a) measuring a transit delay between the two nodes at different times resulting in a plurality of transit delay measurements;

5 b) calculating the jitter among the plurality of time delay measurements; and

c) determining if the jitter exceeds a predetermined threshold value.

In a fourth embodiment, a method of determining a jitter between two transit delay measurements between two nodes, the method comprising:

calculating the jitter based on

$$J(A,D,t) = D(A,D,t_2) - D(A,D,t_1))$$

where

15 $J(A,D,t)$ is the jitter between the two transit delay measurements;

$D(A,D,t_1)$ is one of the two transit delay measurements taken at time t_1 ;

$D(A,D,t_2)$ is the other of the two transit delay measurements taken at time t_2 ; and

20 A and D are the two nodes between which the transit delay is measured.

In a fifth embodiment the invention provides a method of determining a total jitter between a start node and an end node in a network, the method comprising:

a) determining interim jitters in transit delays between adjacent nodes in a communications path between the start node and the end node;

30 b) calculating the total jitter in transit delays between the start node and the end node by adding up the interim jitters.

In a sixth embodiment the invention provides a method of determining a jitter between a plurality of

transit delay measurements between two nodes, the method comprising :

calculating the jitter based on

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$$J(A,B) = \frac{\sqrt{\sum_{i=1}^M D(A,B,i)^2}}{\sum_{i=1}^M D(A,B,i)}$$

where

J(A,B) is the jitter between the plurality of transit delay measurements;

10 D(A,B,i) is the ith transit delay measurement among the plurality of transit delay measurements; and

M is the number of transit delay measurements.

In a seventh embodiment the invention provides a method of determining a signal processing time in a node, the method comprising:

15 a) determining at least one round trip delay time of a transmission between a node A and a node K;

b) determining a round trip delay time of a transmission between a node B and a node K;

20 c) determining a lowest recorded value for the round trip delay time between node A and node K;

d) calculating the signal processing time through node A according to:

$$P(A) = R(K,B) - \text{minimum } (R(K,A))$$

where

25 P(A) is the signal processing time through node A;

R(K,B) is a round trip delay time between node

B and node K; and

(minimum (R(K,A))) is the lowest recorded value for the round trip delay time between node A and node K.

5 Brief Description of the Drawings

A better understanding of the invention may be obtained by reading the detailed description of the invention below, in conjunction with the following drawings, in which:

10 Figure 1 is a topology of a portion of a network showing the connections between different nodes; and

15 Figure 2 is a topology of a portion of a hierarchical network showing the connections between different nodes.

Figure 3 is a topology of a mesh network showing the connections between different nodes.

Description of the Preferred Embodiment

20 Referring to Fig. 1, a sample network 10 consisting of nodes K1, A1, B1, C1 is illustrated. In executing the following methods, it is preferred that the topology of the network be known. US Patents 5,933,416 and 5,926,462 disclose such methods for
25 determining a network topology. These methods are well suited for practitioners of the current invention.

30 To determine the transit delay between two nodes, a first node A1 and a second node B1, using a common node K1, which functions as a standard reference node from which all measurements are taken a number of assumptions can be made for simplicity.

Let $R(K1, A1, t)$ be the round trip delay from the reference point $K1$ to the node $A1$ measured at time t .

It is assumed that the delays are symmetric, i.e., that the delay from a device $K1$ to a node $A1$ is the same as the delay from node $A1$ to node $K1$.

Thus,

$$D(K1, A1, t) = D(A1, K1, t)$$

where $D(K1, A1, t)$ is the delay between a signal leaving node $K1$ directed towards node $A1$ and the same signal being received at $A1$.

From the above assumption,

$$D(K1, A1, t) = R(K1, A1, t) / 2$$

Now let there exist a device $B1$ in the network such that device $A1$ lies on the path from $K1$ to $B1$.

This network is illustrated in Fig. 1.

Thus,

$$D(K1, B1, t) = D(K1, A1, t) + D(A1, B1, t)$$

$$\text{i.e. } D(A1, B1, t) = D(K1, B1, t) - D(K1, A1, t)$$

$$= (R(K1, B1, t) - R(K1, A1, t)) / 2$$

If the path from $A1$ to $C1$ leads through $B1$, then

$$D(A1, C1, t) = D(A1, B1, t) + D(B1, C1, t) \quad (1)$$

This means that the delay between $A1$ and $C1$ is the sum of the interim delays between adjacent nodes on the path from $A1$ to $C1$. Thus, the delay between $A1$ and $B1$ ($D(A1, B1, t)$) added to the delay between $B1$ and $C1$ ($D(B1, C1, t)$) is the total delay between $A1$ and $C1$. We can find the delay between $A1$ and $B1$ using the above formula and we can similarly find the delay between $B1$ and $C1$ using similar techniques.

We can therefore find the delay between a pair of nodes A1 and C1 based on measurements taken from a common node K1.

5 From the above, the transit delay between any two nodes in a network can thus be found using measurements made from a common node.

10 It should be noted that the method outlined above is best suited for hierarchical networks. Such a hierarchical network is illustrated in Figure 2. In hierarchical networks, there is only one path from one node to another. Thus, as can be seen from Figure 2, in the network 20, the only path from node A to node D is through nodes B and C.

15 However, it should also be noted that the method above can be adapted for use with mesh networks such as network 30 shown in Figure 3. The network in Figure 3 is not a hierarchical network in that multiple paths are possible between two nodes. For example, the path from node K to node R can be through the nodes K, A, Q and R or through the nodes K, A, B, Q, R, or through the nodes K, A, B, C, D and R.

20 To determine the delay between nodes K and R, we know from the above that this delay is the sum of the interim delays between adjacent nodes which are in the path from node K to R. Thus, once the delays between such adjacent nodes are determined, the delay between nodes K and R, via a certain path, can easily be found. To find such interim delays between adjacent nodes, measurements of transit delay can be made from different common nodes. In Figure 3, any of the nodes can be used as a common node from which delay measurements are made. Suitable combinations of node pairs can be used to determine the transit delay between nodes. Since the

topology of the network is known, this would simply be a matter of choosing which nodes to combine. Thus, again using Figure 3, the delay between nodes A and Q can easily be determined as they are adjacent and directly connected nodes. The same can be said for node pairs Q-R, B-Q and D-R. So, to find the delay between nodes K and R, using a path which goes through nodes A and Q, would be a matter of adding the transit delay between nodes K-A, A-Q and Q-R.

It can therefore be seen that any suitable sized portion of a network is a hierarchical network. While the network of Figure 3 is a mesh network as a whole, portions are hierarchical. Two directly connected adjacent nodes are the smallest hierarchical network. Thus, the subnetwork comprising nodes T, S and R is a hierarchical subnetwork arm of the mesh network. Similarly, subnetwork Q-B is hierarchical along with subnetwork X, Y and Z.

By subdividing a mesh network into smaller hierarchical subnetworks and moving the common or reference node to nodes within such subnetworks, the method above is clearly applicable to mesh networks. Iterative application of the above method to the hierarchical subnetworks eventually results in the measurement of transit delay between adjacent nodes.

Ideally, the signal sent from the common node, usually a network management computer (NMC) to a node being queried is one that does not require extensive processing time at the node being queried. This signal can be a ping or its equivalent which, when sent from a device A to device B, should result in a corresponding reply signal being sent from device B to device A. The

corresponding reply signal need not be similar to the original signal received by B.

5 In cases where the processing time at a node is appreciable, it is assumed that this time is a constant and is adjusted for in delay calculations concerning that node. We outline below one way of determining this processing time:

10 Consider two adjacent nodes A1 and B1 which are connected such that the path to B1 from the NMC, K1, goes through A1 as in Figure 1. Let $R(K1, B1)$ and $R(K1, A1)$ be the round trip delays to nodes B1 and A1 from K1 respectively. If, at any given time, $R(K1, B1)$ is less than the minimum ever recorded value of $R(K1, A1)$ then this discrepancy is attributed to the extra processing
15 time at node A1 and hence we deduce the processing time of A1, $P(A1)$, as

$$P(A1) = R(K1, B1) - \text{minimum}(R(K1, A1))$$

This processing time is then subtracted from all delay calculations involving node A1. For example:

20
$$R(K1, A1) = R(K1, A1) - P(A1)$$

To determine the variance or jitter in transit delay between nodes, multiple determinations of transit delay between two nodes need to be made. Once this data is collected, variance or jitter can be found.

25 Even with this assumption, we can still generalize jitter calculations. We can compute the jitter $J(A, C)$ between nodes A and C over M samples of $D(A, C, t)$. When $M = 2$, we compute the instantaneous jitter $J(A, C)$ as

30
$$J(A, C) = D(A, C, t_2) - D(A, C, t_1) \quad (2)$$

where time $t_2 > t_1$. In this case, we preserve the sign or direction of change in transit delay.

In the case of M samples where $M > 2$, we compute the jitter as the variance over the M samples using the formula:

5

$$J(A,C) = \frac{\sqrt{\sum_{i=1}^M D(A,C,i)^2}}{\sum_{i=1}^M D(A,C,i)} \quad (3)$$

As an example, a portion of a network with a topology as shown in Fig. 2 can be used. In this network, node K is the reference point (or the NMC) and we want to compute the delay and the jitter in the communications path A - D.

Let the NMC (node K) send signals to nodes A, B, C and D at times t_1 and t_2 and obtain the following round trip values (all in milliseconds). (Note: It is assumed that time $t_2 > t_1$)

15

	time t_1	time t_2	
R(K,A,t) =	9.2	9.8	milliseconds
R(K,B,t) =	7.6	6.8	milliseconds
R(K,C,t) =	3.4	3.2	milliseconds
20 R(K,D,t) =	4.6	4.8	milliseconds

where, as above, $R(A,B,t)$ is the total time elapsed between node A sending a signal to node B at time t and node A receiving a corresponding signal from node B where the corresponding signal is sent by B only after the receipt of the original signal from node A.

25

Then the following values can therefore be found (again using the notation introduced above and from (1)):

$$\begin{aligned} D(B,A,t_1) &= (9.2 - 7.6) / 2 = 0.8 \text{ ms} \\ D(C,B,t_1) &= (7.6 - 3.4) / 2 = 2.1 \text{ ms} \\ D(C,D,t_1) &= (4.6 - 3.4) / 2 = 0.5 \text{ ms} \end{aligned}$$

Therefore, the delay between node A and D can be found as:

$$\begin{aligned} D(A,D,t_1) &= D(B,A,t_1) + D(B,C,t_1) + D(C,D,t_1) \\ &= 0.8 + 2.1 + 0.5 \\ &= 3.4 \text{ ms} \end{aligned}$$

For time t_2 , similar calculations can be carried out:

$$\begin{aligned} D(B,A,t_2) &= (9.8 - 6.8) / 2 = 1.5 \text{ ms} \\ D(C,B,t_2) &= (6.8 - 3.2) / 2 = 1.8 \text{ ms} \\ D(C,D,t_2) &= (4.8 - 3.2) / 2 = 0.8 \text{ ms} \end{aligned}$$

A second total transit delay between nodes A and D is therefore:

$$\begin{aligned} D(A,D,t_2) &= D(B,A,t_2) + D(B,C,t_2) + D(C,D,t_2) \\ &= 1.5 + 1.8 + 0.8 \\ &= 4.1 \text{ ms} \end{aligned}$$

We can now estimate jitter in the path A - D as (from (2))

$$\begin{aligned} J(A,D) &= (D(A,D,t_2) - D(A,D,t_1)) \\ J(A,D) &= 0.7 \text{ ms} \end{aligned}$$

The above jitter calculations are based on two transit delay measurements. However, long term jitter or variance in transit delay between two nodes can

easily be found using well known statistical methods. Such variance, whether long term or between two measurements, can be used as a measure of the quality of communications between two nodes.

5 Because the variance is essentially a measure of the extent a transit delay may deviate from the mean transit delay, by comparing this variance with a predetermined threshold, one can measure how bad the delay can be. If the application being used on the
10 network cannot tolerate a specific maximum transit delay or a specific maximum jitter, then the network is not suitable for this application. Alternatively, as long as the network is operating within set parameters, as measured by the transit delays and jitter, the network
15 can be considered healthy. If the transit delays or the jitter measurements do not meet a predetermined threshold, an alarm can be indicated to thereby alert the network operators that problems in the network performance need to be addressed.

20 The above methods can be run as a software module within a main software process residing on a Network Management Computer (NMC) that executes the methods described in US Patents 5,933,416 and 5,926,462. This main process receives information about the devices
25 in the network from a second software process, which periodically gathers information directly from the devices or nodes in the network. The main process uses this information to construct the physical topology of the network. A software module is then used to
30 periodically send signals to the devices in the network and to accurately record the associated round trip delays. The signal used here is the 'ping' operation. The processing time for this operation is negligible (or

constant) with respect to the transmission times over the network between the NMC and the node. This information is passed on to the main process which uses it in conjunction with the physical topology of the network to compute delays on a device as described above. For every node A being monitored, the main process would compute delays $D(A,B)$ and $D(C,A)$ where B and C are nodes that are directly connected to A, i.e., if a graph is used to represent nodes and edges represent direct physical connections between devices, B and C would be adjacent nodes to A with edges between B and A and C and A.

$D(A,B)$ and $D(C,A)$ are computed for every device A being monitored by the main software process. These calculations are stored in an internal device database as well as a statistical database. The internal device database stores the most recent $D(A,B)$ values for a device whereas the statistical database stores the history of $D(A,B)$ values over a period of time. Average $D(A,B)$ values for 5-minute and 1-hour intervals over the previous two days and 1-day intervals for older samples are stored in the statistical database.

Instantaneous jitter values $J(A,B)$ (between two consecutive delay samples) are also computed, along with simple statistical measures over them such as the minimum, maximum and average, and stored in the two databases as described above for $D(A,B)$. Long term jitter is not stored explicitly in the database but rather computed on demand from the $D(A,B)$ values stored in the statistical database. These values of $J(A,B)$ and $D(A,B)$ are read in by a third software process which produces reports. These values can be used to generate

alarms based on comparisons with user specified alarm thresholds. These values can be graphically displayed such as, for a certain threshold, all points in the network where the jitter and delay exceed the threshold are highlighted in a certain colour on a graphical map displaying the topology of the network. The user can change thresholds and at a glance, see the non-conforming portions of his network.

The user may also specify two devices A and B (not necessarily connected directly to each other) over which the user would like to see delays $D(A,B)$ and jitters $J(A,B)$ computed and alarmed. This is very useful in identifying the total delay and jitter experienced by a user on device A who is sending signals to device B. Since applications usually specify minimum requirements for acceptable service in terms of the end nodes involved in the application, the above calculation becomes essential.

A person understanding the above-described invention may now conceive of alternative designs, using the principles described herein. All such designs which fall within the scope of the claims appended hereto are considered to be part of the present invention.